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A GAGE FOR INVESTIGATING THE INTERNAL STRUCTURE OF THE COLUMNS PRODUCED BY SHALLOW UNDERWATER EXPLOSIONS (U)

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A GAGE FOR INVESTIGATING THE INTERNAL STRUCTURE OF THE COLUMNS PRODUCED BY SHALLOW UNDERWATER EXPLOSIONS

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ABSTRACT: Knowledge of the internal structure of the water column produced by a shallow underwater nuclear explosion and of the blowout of explosion products is needed for the calculation of radiological and air shock effects. A piezoelectric gage is proposed to study the internal column structure and blowout on scaled high explosive tests. The different parameters which the gage will sense as pressure changes are discussed. Design requirements and plans for use of such a gage are summarized.

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EXPLOSIONS RESEARCH DEPARTMENT
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This report discusses the use of a piezoelectric gage to study the internal structure of the water column produced by a shallow underwater explosion. It represents a portion of the continuing program of investigating the surface phenomena resulting from both conventional and nuclear underwater explosions. This work was supported by WEPTASK No. RE01 ZA732/212 9/F008-21-003, Delivery Criteria for Underwater Nuclear Weapons.

The authors wish to thank Dr. H. G. Snay, who originally conceived the idea of such a gage. The authors also wish to thank R. L. Willey, B. W. Scott, and C. W. Mangold for constructing the gage and continually improving its design, and J. F. Pittman for his assistance with the electronics.

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1. INTRODUCTION

One phase of underwater explosion phenomenology which has undergone little investigation is the internal structure of the water column produced by a shallow burst. Detailed knowledge of the column is particularly important on nuclear bursts because it influences radiological as well as air shock wave effects. Investigations of the external structure of scaled high explosive columns have been conducted by the analysis of photographic records (reference 1); however, little is known of the internal characteristics. This report will cover briefly the present state of knowledge of the structure of the column and the feasibility of using a piezoelectric gage to study its internal structure. Such a gage has been constructed and is currently undergoing testing at this Laboratory's facility at Stump Neck, Maryland.

1.1 Surface Phenomena of a Shallow Underwater Burst

The surface phenomena of shallow underwater explosions are caused primarily by two effects: the shock wave produced by the explosion and the mass-motion of the water caused by the expanding bubble of gaseous explosion products. When the shock wave reaches the water surface, it is almost entirely reflected as a tension wave. As a result, a particle velocity is imparted to the water surface, and a rising dome of spray is formed. As the shock wave does not undergo total reflection, its energy is partially transmitted into the air and an air shock wave rises ahead of the spray dome. In addition, the tension wave produced by the reflection produces a region of cavitated water beneath the surface.

Shortly after the appearance of the spray dome, the effect of the expanding gas bubble can be seen. This generally appears as a vertical and radial growth on the side of the spray dome, distorting its smooth outline. The rising jets of the water column quickly overtake the spray dome and reach relatively great heights, depending on the charge weight and depth of the explosion. The spray dome, directly transmitted shock wave, and effect of the expanding bubble are illustrated in Figure 1.

As the layer of water above the explosion is pushed up by the expanding gas bubble, the small cavitation bubbles formed by the downward moving tension wave probably collapse. The entire layer becomes progressively thinner until it finally ruptures. If the depth of burst is sufficiently shallow the layer of water, or seal, will rupture while the pressure of the gases in the bubble is greater than atmospheric pressure, and the explosion products will be released to the atmosphere. This is termed "blowout". As the depth of burst increases, the pressure of the gas at the time of rupture becomes lower and may even become less than atmospheric. In this case, an inflow of air will occur when the seal ruptures. This inflow is called "blow-in". The term "venting" has also been used to describe the rupture; however, this term is ambiguous and can represent either case.

The residue of a high explosive, such as TNT, usually contains a great deal of carbon. Thus, blowout will be evidenced by blackness on the cavitation-whitened water. The time of appearance of this blackness is assumed to be the time of rupture of the water seal. For a very shallow explosion, the ejection of the gases will be rapid and a black smoke crown will appear at the top of the column.

1.2 Blowout Criteria

Existing photographic records have provided a simple method for evaluating blowout. The criterion used is the ratio of maximum smoke crown diameter (S_{max}) to maximum column diameter (D_{max}). (These maxima do not necessarily occur simultaneously.) If this ratio approaches unity, it would seem probable that most of the explosion products are contained within the column and blowout does not occur. This is made evident by the following observations:

(1) At reduced charge depths less than about $\lambda_d = 0.2$ ft/lb$^{1/3}$*, the column is all but non-existent, surface phenomena consisting mainly of a very dark ball of smoke and water above the water surface.

(2) At reduced depths greater than about $\lambda_d = 0.2$ ft/lb$^{1/3}$, the column and smoke crowns tend to become distinct entities. With increasing depth, the column reaches a greater height before the smoke crown forms. Eventually, the profile of the smoke crown becomes more and more elongated in the vertical direction and smaller in the horizontal direction, finally becoming indistinguishable (in diameter, not necessarily color) from the column between $\lambda_d = 1.25$ and 1.50 ft/lb$^{1/3}$. A typical water column and smoke crown for a blowout condition are shown in Figure 2.

* The reduced charge depth, λ_d, is defined as the depth of burst (measured to the center of the charge) divided by the cube root of the charge weight, $\frac{d}{W^{1/3}}$, in ft/lb$^{1/3}$.

Maximum column and smoke crown diameters for a range of reduced depths are tabulated in reference 1. The ratio of these parameters is plotted as a function of reduced charge depth in Figure 3. To normalize charge depths, some adjustments in the tabulated data were made. Many of the charges were either cylinders or flat discs. For these, the reduced depths used in Figure 3 are those of the center of a spherical charge of the same weight whose top surface is the same reduced distance beneath the water surface as the top of the actual charge. This correction is employed because it is believed that the thickness of the water layer above the charge is a more pertinent parameter than the depth of the center of detonation in the consideration of the blowout mechanism.

The large amount of scatter in Figure 3 is caused by several factors. First, the correction described above is only an approximation. If the cylinder was nearly cubic in shape, then this correction changed the reduced depth only slightly. However, as the shape of the charge became more squat or elongated, the correction became greater. Undoubtedly, the corrected values are better than the uncorrected values of charge depth; however, how closely they approximate an actual spherical charge is unknown. This effect will be eliminated by the use of spherical charges of various weights in future work.

Perhaps an even more important factor is the condition of the water surface at the time of detonation. If the water surface is rough, the depth of water above the charge varies, depending on whether a crest or trough of a wave is over the charge. The effect of surface roughness becomes increasingly important as the depth of water decreases, as the percentage change in water depth becomes large for a given wave amplitude. The shape of the smoke crown, which is always irregular, is probably strongly affected by surface roughness.

In addition, the extreme edges of the crown may be irregular puffs of smoke, whose position is strongly influenced by internal and atmospheric turbulence.

In spite of the large amount of scatter, Figure 3 does indicate a trend toward decreasing S_{max}/D_{max} with increasing reduced depth. No pronounced discontinuity appears; however, a mean curve would probably show a tendency to level off between reduced charge depths of 0.5 and 0.7 ft/lb$^{1/3}$. Because of the lack of data in this region, however, no definite conclusion can be reached.

This method represents a first attempt to study the phenomenon of blowout. It is inadequate for several reasons. First, the method considers only the extent of the smoke crown, which can be affected by variables other than the rupture of the seal and the pressure of the bubble gases at the time of rupture. The time of appearance of the black smoke is also important and is not considered in this method. It is probable that the transition région from blowout to blow-in is not well defined and that in this region criteria such as surface roughness must also be considered. While the method will serve as an aid in determining the transition region, it must be combined with other methods to give an adequate interpretation.

1.3 Taylor Instability

Another effect occurring with a rough surface is that of Taylor Instability. The theory of Taylor Instability (reference 2) treats the accelerated motion of the common surface of two fluids of different densities, using the standard equations of hydrodynamics. Such a surface is said to be stable if, during some kind of motion, irregularities tend to smooth out as the motion proceeds. On the other hand, it is said to be unstable if the irregularities grow during the motion.

The layer of water over an underwater explosion bubble may be considered as a thin layer moving between the bubble gases below and the atmosphere above (reference 3). At least two phases of the motion of the water seal occur during the expansion of the bubble. Initially, the expansion of the bubble accelerates the water seal upward at a rate much exceeding the downward acceleration of gravity. In this case, the bubble side of the layer is unstable, and the atmosphere side is stable. Later, the rate of expansion of the bubble has decreased considerably, and the resultant acceleration of the layer is downward. Thus, for the later part of the bubble expansion, the upper surface of the layer is unstable, and the bubble side is stable. This instability is evidenced by the formation of jets on the side of the rising column. The troughs which develop on the outer surface of the layer may possibly penetrate to the inner surface, providing a path for penetration of air into the bubble.

1.4 Summary

From the foregoing discussion, it can be seen that current knowledge of the structure of the water columns produced by shallow underwater explosions is mainly qualitative. Previous work has been primarily concerned with the external structure as a criterion for blowout. This has given an approximate region where blowout ceases. A study of the internal structure, combined with a more detailed study of the external structure, would not only give a better idea of the transition region but might also indicate the density of the spray in the column, the thickness of the water seal, the amount of spray above this seal, the point of rupture as a function of height above the charge, and whether blowout or blow-in occurs.

2. ESTIMATES OF PRESSURE AT THE GAGE

As the column rises, it is completely shrouded by a layer of water droplets produced by the reflection of the shock wave. The size of these droplets will depend on the depth and size of the explosion. Inside this mist will be the seal of continuous water, possibly containing a cavitated region, and finally, the gas bubble. A conception of the structure of the surface phenomena of a shallow underwater explosion is shown in Figure 4. When the seal ruptures, it probably does so initially at the top, leaving the sides of the seal intact. Although not a part of the water column, the transmitted shock wave, which is preceding the rise of the column, should be kept in mind.

It seems feasible that a piezoelectric probe, suspended so that it would be engulfed by the rising water column, would indicate the existence and magnitude of the various parameters just mentioned. As a piezoelectric material measures changes in pressure, it is necessary to consider these parameters in terms of pressure.

2.1 Air Shock Wave

The first phenomenon to reach the gage is the transmitted shock wave. Actually, for shallow bursts, there are at least two air shock waves - the transmitted shock wave and the shock wave produced by the piston action of the rising water column. In general, the latter is the stronger of the two (reference 4).

When the probe is centered over surface zero, the situation is that of a plane shock wave being reflected from a rigid plane boundary. The shock waves are actually curved; however, if the end of the probe covers a small area, the portion of the shock cut off by the gage may be considered to be plane. Edge effects will be negligible if the crystal element constitutes only the central portion of the end area of the gage and cannot sense the pressure variations at the edges of the gage.

The equation which governs the reflection of a plane shock at a rigid plane boundary is (reference 5):

$$\frac{P_f}{P_a} = 2\left(\frac{7P_o + 4P_a}{7P_o + P_a}\right) \tag{2.1}$$

where: P_a = incident shock wave overpressure

P_r = reflected shock wave overpressure

P_o = atmospheric pressure

No measurements of air shock wave pressures directly above surface zero are available; however, the peak pressure recorded five feet above and three feet horizontally from surface zero of a 1-lb TNT charge fired at a reduced depth of 0.54 ft/lb$^{1/3}$ was 5 psi (reference 4). Assuming an atmospheric pressure of 15 psi, Equation (2.1) predicts a pressure of 11.4 psi will be sensed by the gage.

Although not a purpose of the gage, it would be possible to use it to measure the shock wave pressure above surface zero. With the current gages used to measure air blast (reference 4), this is nearly impossible. These gages are generally too large and too fragile to withstand the impact of the water. A gage designed for the study of the structure of the column would of necessity be built to withstand this impact. The limiting factor would be the response of the instrumentation, as the time it would take this shockwave to pass over the gage is probably only a few microseconds at most.

2.2 Spray

The next phenomenon to reach the gage is the layer of spray produced by the reflection of the underwater shock wave at the water surface. If the droplets are smaller than the face of the gage but large enough to cross the air stream, the droplets will strike the gage and flow radially outward from the point of impact. The impact pressure of a single droplet sensed by the gage is (reference 6):

$$P_d = \frac{\alpha}{2} (\rho c v) \qquad (2.2)$$

where: P_d = impact pressure of droplet

ρ = density of water

c = velocity of sound in water

v = velocity of the center of gravity of the droplet

α = correction factor for the curvature of the droplet.

Values of α have been obtained empirically (reference 6) and it was found that for high velocity droplets the value was nearly unity. Thus, within the range of velocities expected (see Section 2.3.3) the pressure from the impact of the droplet should be $1/2 \rho c v$. Note that this is one half the pressure of continuous water (see Section 2.3.1).

The duration of the impact pressure is very short and is dependent on the size of the droplet and its velocity. Experimental evidence indicates that the total duration of the impact pressure is equal to the time it takes the droplet to transform into radial flow (reference 6). Thus, a droplet 0.5 inches in diameter which is moving at a velocity of 1,000 ft/sec would produce an impact pressure lasting 41.5μsec.

The velocity of the center of gravity of the droplet decreases rapidly as the motion changes from vertical to radial flow. The impact pressure-vs-time curve would therefore appear as a sharp spike with a peak pressure predicted by Equation (2.2) where v is the velocity of the droplet at the instant of impact. The curve would then decay as the radial flow becomes dominant.

The pressure which the gage would sense is complicated by the concentration of the droplets in the spray. It is likely that several droplets may strike the gage before the pressure returns to zero after the impact of a single droplet. Also, if the water droplets are too small, they will follow the streamlines rather than pass through them and strike the gage. Calculations indicate that the individual droplets are sufficiently large to strike the gage rather than flow around it, for explosions of 1-lb and greater.

2.3 Water Seal

The seal of water which contains the bubble contents is a continuous sheet of water. The pressures which the gage should sense are two in number: the impact of the water hitting the gage and that caused by the flow of water around the gage.

2.3.1 Impact Pressure. The impact pressure is caused by the sudden stopping of a fluid in motion and is sometimes referred to in hydrodynamics as the "water hammer effect." At the instant of impact, the motion of the layer in contact with a rigid body (in this case the face of the gage) is suddenly stopped. The water in this layer must be compressed, for if it were not, the pressure would be infinite between the rigid body and the layer of water. This region of compressed water travels rapidly back through the water as a shock wave. The mass of water compressed in a time dt, is (reference 7):

$$dm = \rho A c \quad dt \tag{2.3}$$

where ρ = density of water

A = surface area of impact

c = speed of sound in water

The sudden stopping of the water is described by Newton's third law:

$$F\,dt = m\,dv \tag{2.4}$$

where $F\,dt$ = impulse supplied by the gage

$m\,dv$ = total momentum change suffered by the water.

Integrating these two equations over a time, t, and substituting, the following expression is obtained:

$$Ft = m\,v = (\rho A c t)\,v \tag{2.5}$$

or $$P_i = \frac{F}{A} = \rho c v \tag{2.6}$$

where P_i = impact pressure

2.3.2 Dynamic Flow Pressures. As the water begins to flow around the gage, pressures caused by this flow become dominant. The pressures experienced by an obstacle in a homogeneous flowing fluid are well understood and are given by Bernoulli's equation (reference 8):

$$P_h + \tfrac{1}{2}\rho v^2 + \rho g z = \text{constant along a stream tube} \tag{2.7}$$

where: P_h = hydrostatic pressure

ρ = density of water

v = flow velocity of the fluid

g = acceleration due to gravity

z = vertical length component

The second term in Bernoulli's equation is called the dynamic pressure and the last term is called the potential pressure. From this equation, the stagnation pressure, P_s, is defined (reference 8):

$$P_s = P_h + \tfrac{1}{2}\rho v^2 \tag{2.8}$$

The stagnation pressure is the pressure at a point in a flowing fluid where the flow velocity has been reduced to zero. The dynamic pressure, then, is the increase over hydrostatic pressure necessary to bring the fluid to rest at a stagnation point without loss of energy. If the sensitive face of the plume pressure gage is oriented parallel to the direction of uniform flow at a given point, the gage will sense the hydrostatic pressure - the "containing" pressure applied to a flowing fluid. When the sensitive face of the gage is oriented normal to the direction of flow at a point, the center of the crystal element becomes a stagnation point, and stagnation pressure is sensed.

Potential pressure may be ignored in the current case, since, at the times of interest, there is a negligible amount of fluid above the face of the plume gage.

2.3.3 Estimates of Impact and Stagnation Pressures at Gage. The two equations presented for impact and stagnation pressures which the gage should sense contain only three parameters: density of water, the velocity of sound in water, and the velocity with which the water is moving. The values of the first two parameters are easily obtained. The density of water is 1.99 slugs/ft^3 and the velocity of sound in water is approximately 5,000 ft/sec. The velocity of the rising water column, the third parameter which must be evaluated to obtain estimates of the pressures, cannot be directly obtained, as the sheet of continuous water is obscured by the water droplets in the spray dome.

However, acoustic theory provides an estimate of the initial velocity of the water surface. This can be used to obtain an approximate value of the velocity of the water column. The initial velocity of a particle at the surface directly above the charge is (reference 9):

$$v_o = \frac{2P_m}{\rho c} \tag{2.9}$$

where: P_m = peak pressure in the underwater shock wave.

For TNT, the peak pressure is given by the expression:

$$P_m = 21,600 \left(\frac{W^{1/3}}{R}\right)^{1.13} \tag{2.10}$$

where: P_m = peak pressure, psi

W = charge weight, lbs of TNT

R = distance from the center of the charge, ft.

For a one-lb TNT charge fired at a reduced depth of 1.0 ft/lb$^{1/3}$, Equation (2.9) predicts an initial velocity of 620 ft/sec. The expected impact pressure at this depth therefore is about 43,000 psi and stagnation pressure should be about 2,670 psi. The duration of the impact pressure will be quite brief as the compression wave moves rapidly away from the gage. However, the duration of the stagnation pressure will depend on the thickness of the sheet of water.

It should be noted that Equation (2.9) cannot be used at positions close to the charge. In this region ($P_m > 25,000$ psi), U, the shock front propagation velocity, should be substituted for c. Values for both P_m and U are available from theory (reference 9).

The velocity of the water column will be somewhat lower than that predicted by Equation (2.9) at the location of the gage. This is because the rise of the water droplets is retarded by the effect of gravity and the drag on the droplets. Experimentally, it is possible to measure the velocity of the rising spray accurately by the use of high speed photography.

A plot of the expected impact and stagnation pressures as functions of velocity for water acting as a continuous fluid are shown in Figure 5.

The hydrostatic pressure, P_h, has been ignored in plotting the stagnation pressure as it is insignificant at the pressure levels expected.

2.4 Bubble

The last effect which the gage will sense is the internal pressure of the gas bubble. Assuming that the bubble expands spherically and that this expansion is a reversible adiabatic process, the following equation may be used to estimate the pressure within the bubble (reference 9):

$$E = \frac{P_B V}{\gamma - 1} = \frac{4\pi}{3} \frac{a^3 P_B}{\gamma - 1} \tag{2.11}$$

where: E = energy of the gas

P_B = pressure of the gas within the bubble

V = volume of the bubble

γ = ratio of specific heats

a = radius of the gas bubble

The assumption that the expansion of the gas is a reversible adiabatic process seems reasonable except for the time immediately after detonation, when this expansion is very rapid. The assumption of a spherical expansion is not strictly true; it is more likely that for shallow bursts the bubble is ovoid in shape. However, this assumption seems adequate for the purposes of this report.

The amount of energy available in the bubble is not precisely known. It has been estimated that for TNT, 9 percent of the total detonation energy remains as bubble energy (reference 10). The total energy made available by the detonation of TNT is about 1.47×10^6 ft-lb/lb (1,050 cal/gm); thus the energy of the gas is 1.32×10^5 ft-lb/lb (95 cal/gm). For TNT, γ, the ratio of specific heats is approximately 1.25. The calculated internal pressure of the bubble as a function of bubble radius for a 1-lb TNT detonation is shown in Figure 6.

One effect which should be considered in the measurement of the pressure within the gas bubble is the pyroelectric effect of the piezoelectric crystal. The pyroelectric effect is the development of a charge due to changes in temperature, which set up stresses within the crystal. For tourmaline, a rise of $1^{o}C$ will produce a charge equivalent to 200 psi (reference 9). Little is known of the gas temperature, thus it is difficult to make any prediction as to the magnitude of this effect on the recorded pressure. However, the temperature is not sufficiently high to vaporize the surrounding water, except immediately after detonation. In addition, the assumption of an adiabatic process also means that the temperature decreases as the volume increases. It should be noted that the temperature mentioned in the pyroelectric effect is that of the element, not of the surrounding media. Thus, this effect would only become apparent when the heat of the gas was transmitted to the piezoelectric crystal. It is, therefore, likely that by the time the bubble has expanded sufficiently to reach the probe, its temperature is low enough so as not to affect the recorded pressures significantly. In any case, the measurement of this parameter is not intended to be a primary use of the gage.

2.5 Summary and Conclusions

From the foregoing discussion it is evident that the gage will be subject to a wide range of pressures, varying from an impact pressure of perhaps 40,000 psi down to a gas pressure within the bubble of only a few psi. In addition, the durations of these pressures also vary widely, from the order of microseconds for the impact of a droplet and passage of the air shock wave over the gage to perhaps milliseconds for the passage of the spray. No available electronic circuitry is capable of resolving all these pressures and durations on a single record. Some decision, then, must be made as to the important parameters to measure and those which may be ignored. Another alternative is to fire several shots at the same depth, resolving different parameters on each shot.

3. GAGE DESIGN REQUIREMENTS

The original design for this gage was based on recommendations of Dr. H. G. Snay of this Laboratory. The gage is constructed of a cylindrical aluminum rod which is approximately four feet long and one inch in diameter. The piezoelectric crystal element consists of two discs of tourmaline, each one-half inch in diameter, mounted face-down on the end of the aluminum rod. The output of the gage is about four $\mu\mu$coulombs/psi. The gage is suspended vertically above the charge so that it will be enveloped by the rising water column. The pressure distribution on the face of this type of gage, which is equivalent to a blunt body, has been found to be very close to that given by Equation (2.8) for the area in the center of the gage where the pressure-sensing element is located (reference 11). The components of the gage, and the gage in the field, are shown in Figure 7. In the photograph of the gage in the field, the gage is partially inserted in a 12-foot aluminum pipe for additional support.

3.1 Crystal

The crystal element must be rugged because of the large impacts to which it is subjected when hit by the water. In addition, there are several other criteria which must be considered in the selection of a crystal, such as the magnitude of the signal produced by a given pressure, its sensitivity to hydrostatic pressure, its size, etc. A great deal of study has been made of various piezoelectric materials and their use in measuring transient pressures, especially shock waves produced by explosions. A good summary of information on piezoelectric materials and the multitude of requirements which must be met to produce accurate pressure-time records is given in reference 12. Tourmaline is a piezoelectric material which is used in the study of underwater shock waves and one which meets the needs of the gage. For this reason, tourmaline was selected as the gage element.

3.2 Perturbation of Flow

Another requirement is that the gage perturb the phenomena as little as possible. This produces a truer record of changes in the flow and also minimizes distortion of the phenomena, as it is intended to measure other parameters, such as air blast, on the same shot. In addition, a gage which perturbs the flow only slightly is less likely to be thrown when hit by the water. For these reasons, a one-inch rod was selected to hold the crystal element. The length of the rod, four feet, adds mass to the gage so it is less likely to be accelerated when hit. Piezoelectric crystals are sensitive to accelerations, thus it is important that the gage remain stationary during the passage of the event.

The gage is suspended by light cables rather than being rigidly supported on a beam. This was done to eliminate reflections and vibrations from the beam. Also, it is doubtful a beam could survive a large explosion. The mass of the gage holds it steady during the passage of the events of interest, while the cable allows it to move during the later events which might otherwise damage it.

3.3 Noise

A third and very important requirement of the gage is that it produce as little noise as possible on the pressure records. The noises considered here are spurious signals which are produced at the crystal element itself, although there are other noises produced by the shock wave on the cable and even in the electronic circuitry itself. One source of noise has already been mentioned, that due to acceleration of the crystal. Another is that caused by the internal reflection of the pulse within the gage itself.

Spurious signals can be produced by the reflection of the pulse at the interface between the crystal and the mounting rod.

Acoustic theory indicates that the amplitude of the pressure wave reflected at a rigid boundary is directly proportional to the difference in acoustic impedance* of the two media (reference 5). Keeping this difference small means that the amplitude will be small. As aluminum has nearly the same acoustic impedance as tourmaline, this metal was selected for the mounting rod.

Another source of spurious signals within the gage is the reflection of the pulse at the gage support. When a pressure-producing medium strikes the gage, a pulse will travel the length of the rod, be reflected, and return to the crystal element. The time when this pulse arrives at the crystal depends on the length of the rod and the speed at which the pulse travels in the rod. For aluminum, the speed of sound is about 17,000 ft/sec; thus it will take about 0.47 msec before this pulse appears on the pressure-time records.

4. SUMMARY

A knowledge of the internal structure of the water column produced by a shallow underwater explosion is important for several reasons. In the case of a nuclear explosion the constituents of the column act as a radiation shield. The rising column also produces shock waves in the air which are dependent on its structure and variation with time. The phenomenon of blowout is the result of the rupture of the water seal, which is obscured by the rising spray. Previous attempts to study the rupture of this seal were based on changes in the external features, which proved to be inadequate.

In order to study the internal structure, a piezoelectric gage was constructed. This gage is suspended vertically above the explosion so that it is engulfed by the rising column. As the various constituents pass over the gage, they are sensed as pressure changes. The pressure produced by the spray is believed to be caused by the individual droplets striking the gage. The passage of the water seal produces two pressures, the first an impact pressure produced when the water first strikes the gage and the second by the water flowing around the gage. The final pressure which the gage senses is that of the gases in the explosion bubble. In addition to the constituents of the water column,

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*Acoustic impedance is defined as the product of the density and speed of sound in the medium in question.

the gage will also sense the air shock waves which precede the rising column.

The gage itself was constructed to minimize distortion of the surface phenomena so as not to affect other measurements taken on the same shots. The crystal of the gage is made of tourmaline, a piezoelectric material which has been used in the study of underwater shock waves. It is mounted on a rod made of aluminum, which has about the same acoustic impedance as tourmaline. The gage is suspended by light cables, which allow the gage to move during the later events, preventing damage or destruction of the gage. This type of suspension also permits the use of large charges which a rigid support, such as a beam, could not withstand.

A gage has been constructed and is currently undergoing testing against 1-lb TNT charges. It is planned to use it against explosive charges weighing up to 4,000 lbs. It is expected that, with this range of weights, the variation of column structure with charge size as well as a charge depth may be determined. The use of this information for the prediction of nuclear phenomena will be based on the application of scaling laws and the knowledge of the differences between nuclear bursts and conventional explosions.

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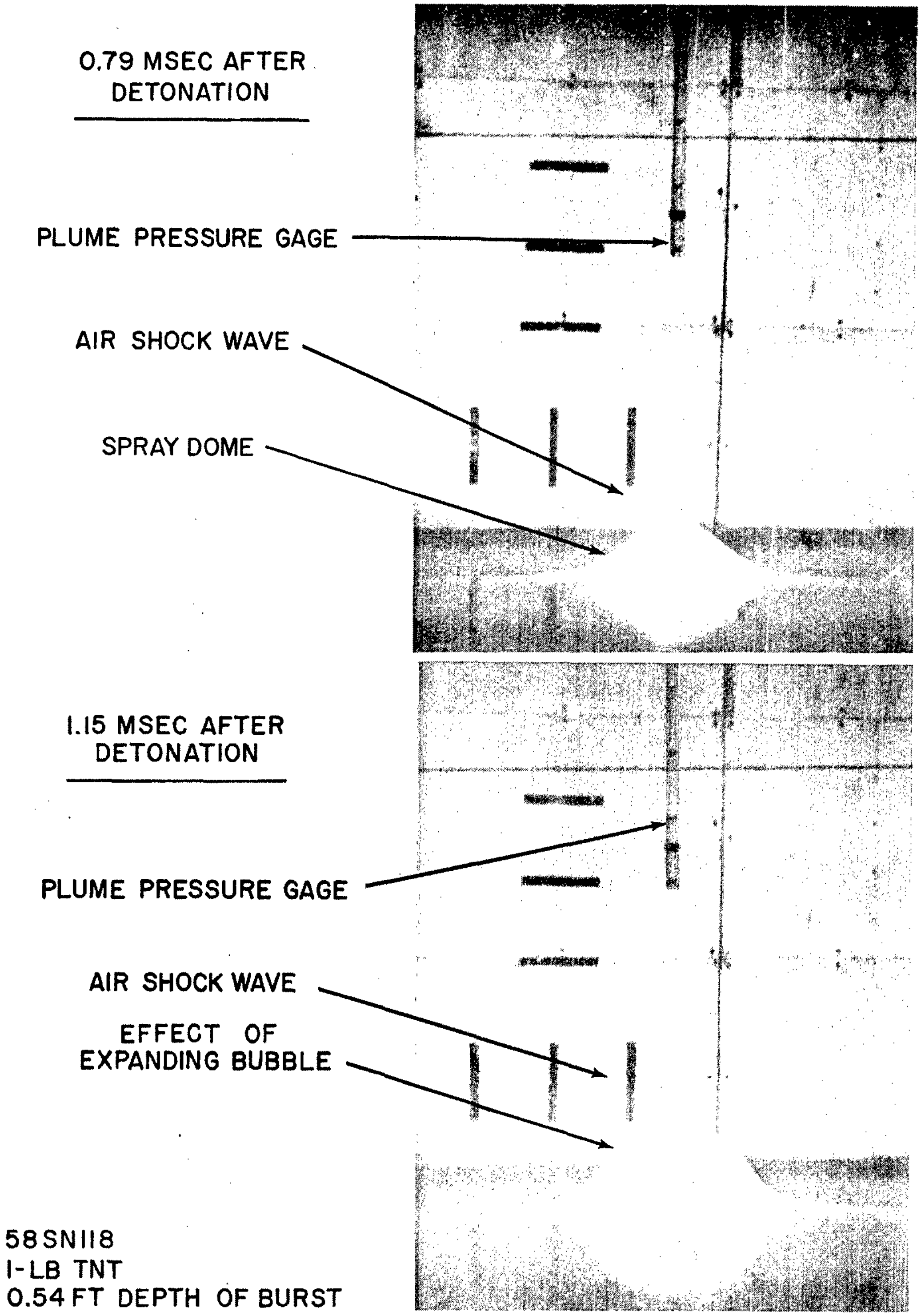
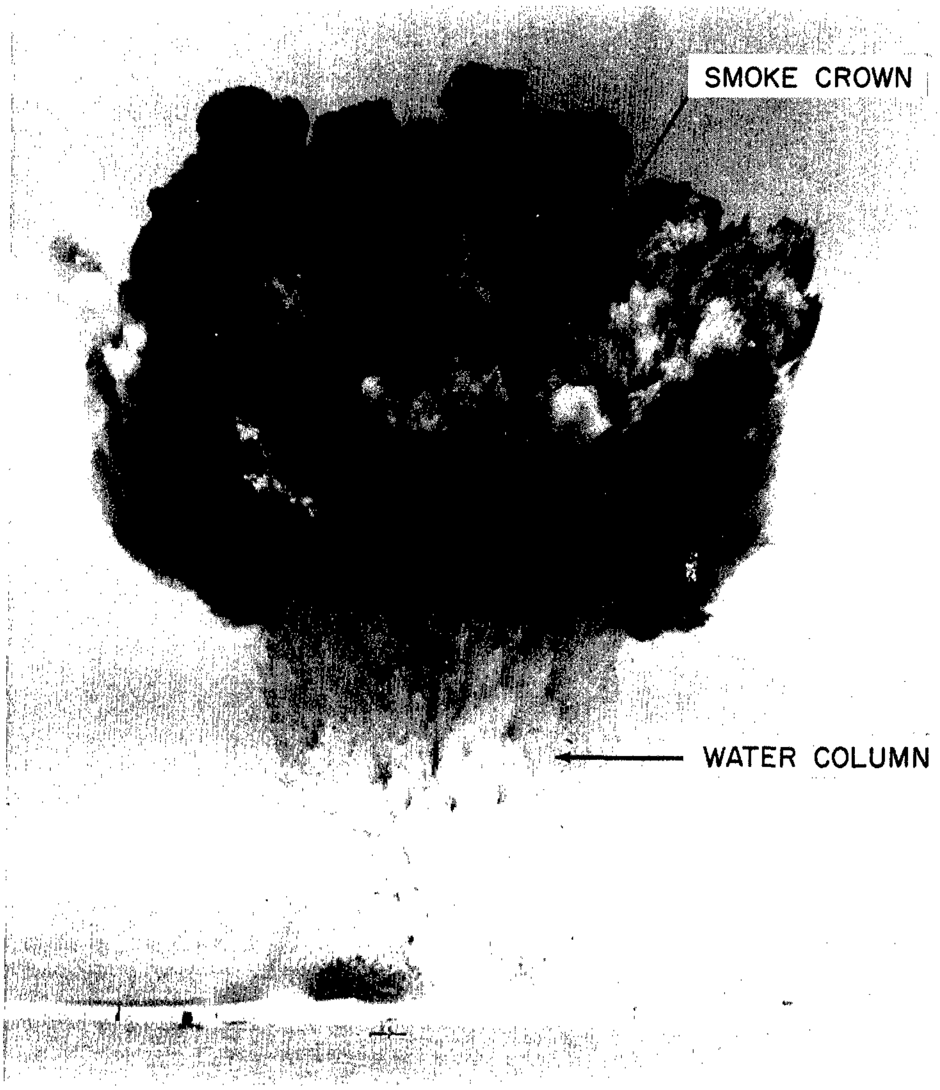


FIG. 1 SURFACE PHENOMENA OF A SHALLOW UNDERWATER EXPLOSION.



SHOT NO. 276 4200 LB TNT
4.33 FT DEPTH OF BURST
$\lambda_d = 0.268$ FT/LB $^{1/3}$

FIG. 2 SMOKE CROWN AND WATER COLUMN

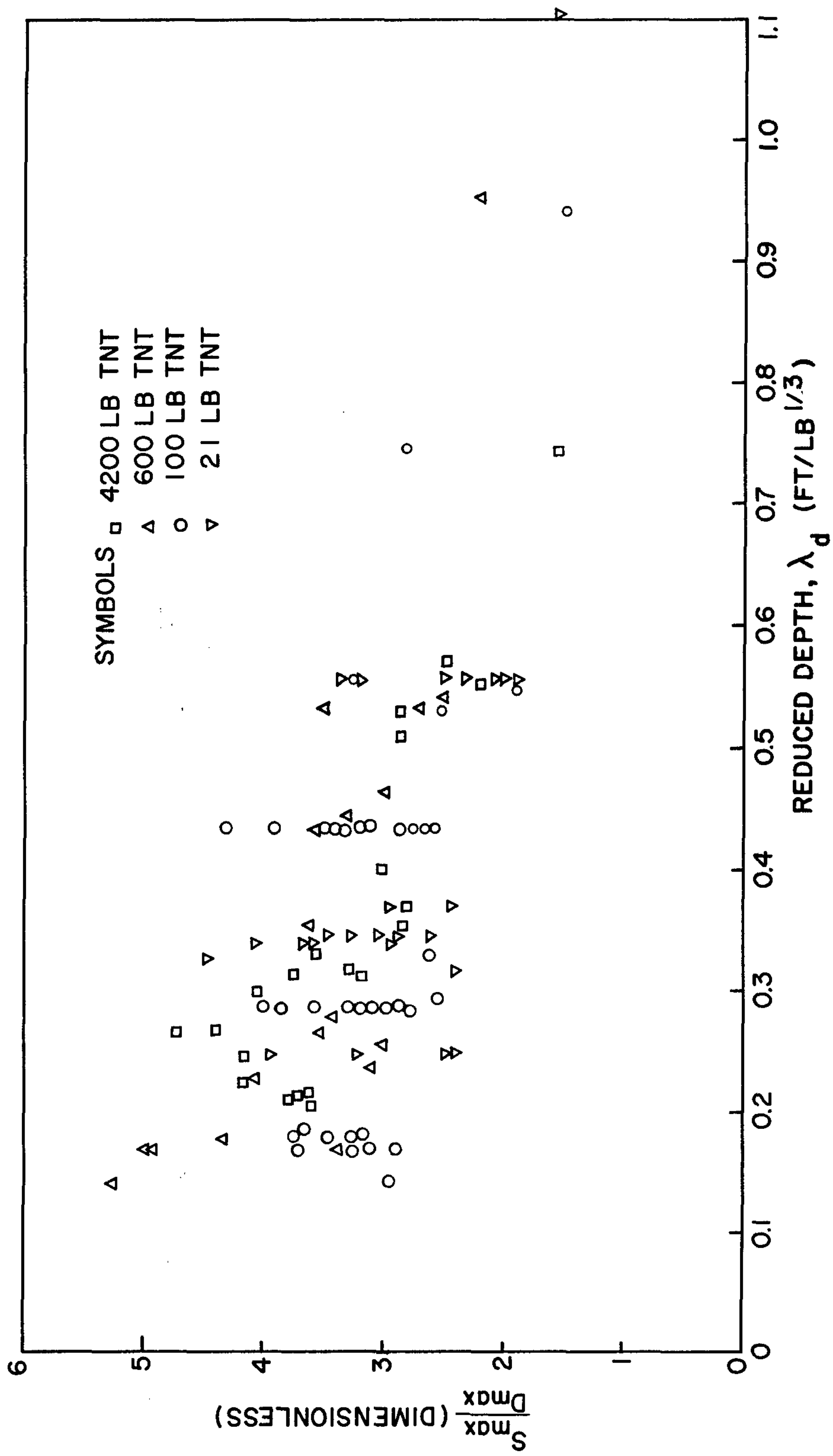


FIG.3 RATIOS OF MAXIMUM SMOKE CROWN DIAMETER TO MAXIMUM COLUMN DIAMETER.

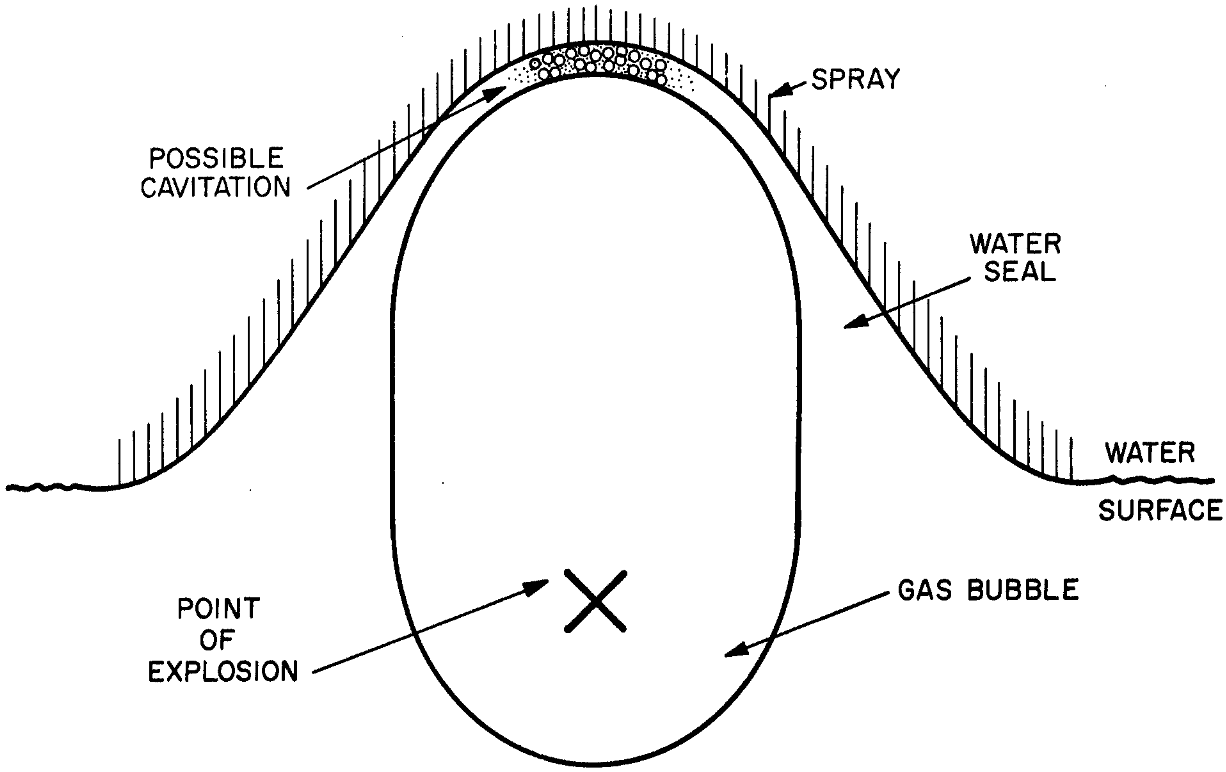


FIG. 4 ASSUMED CROSS-SECTION OF THE SURFACE PHENOMENA OF A SHALLOW UNDERWATER EXPLOSION.

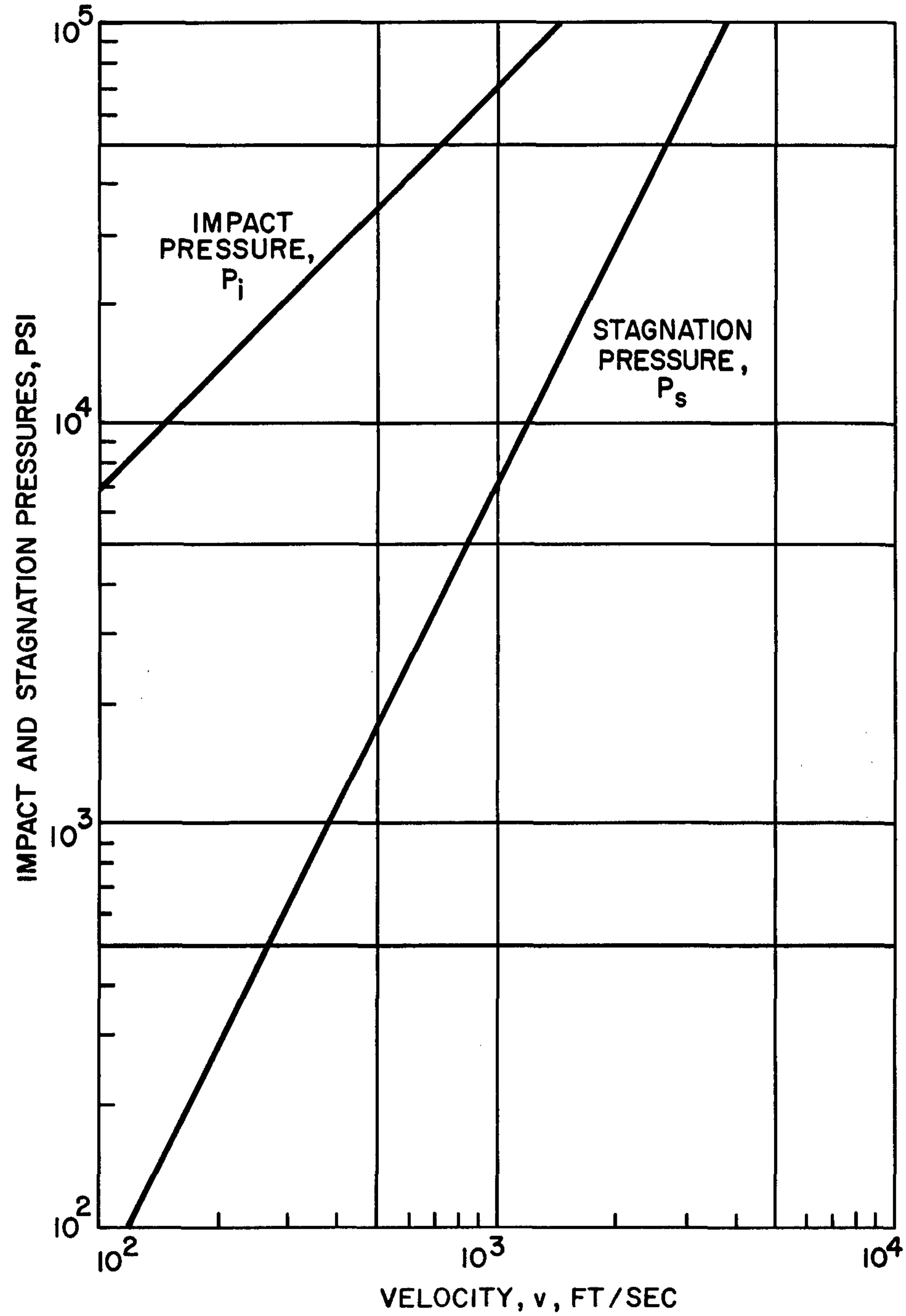


FIG. 5 IMPACT AND STAGNATION PRESSURES VS VELOCITY

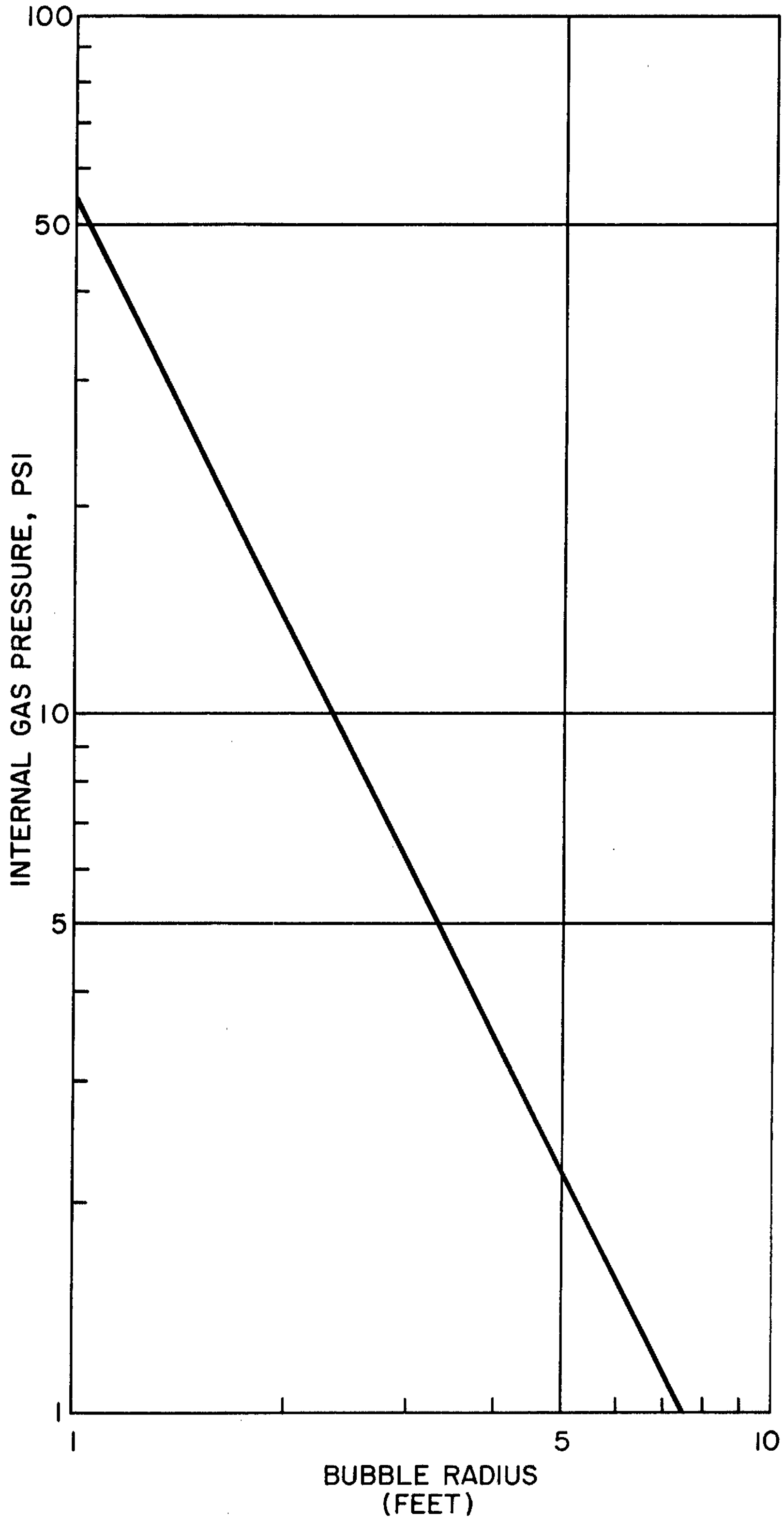
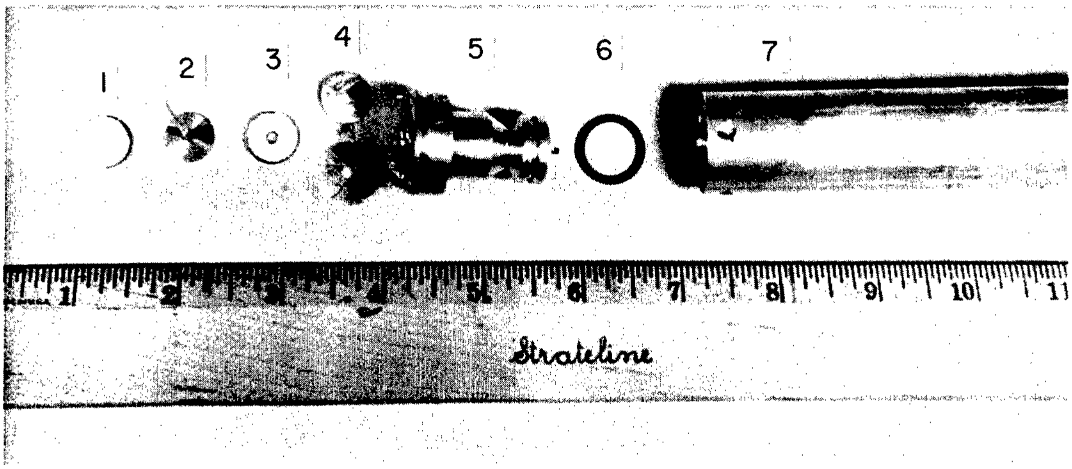


FIG. 6 INTERNAL GAS PRESSURE VS BUBBLE RADIUS FOR A 1-LB TNT EXPLOSION.



COMPONENTS:

1. TOURMALINE CRYSTAL
2. TAB
3. TOURMALINE CRYSTAL
4. FOIL
5. GAGE HEAD
6. "O" RING
7. GAGE BODY

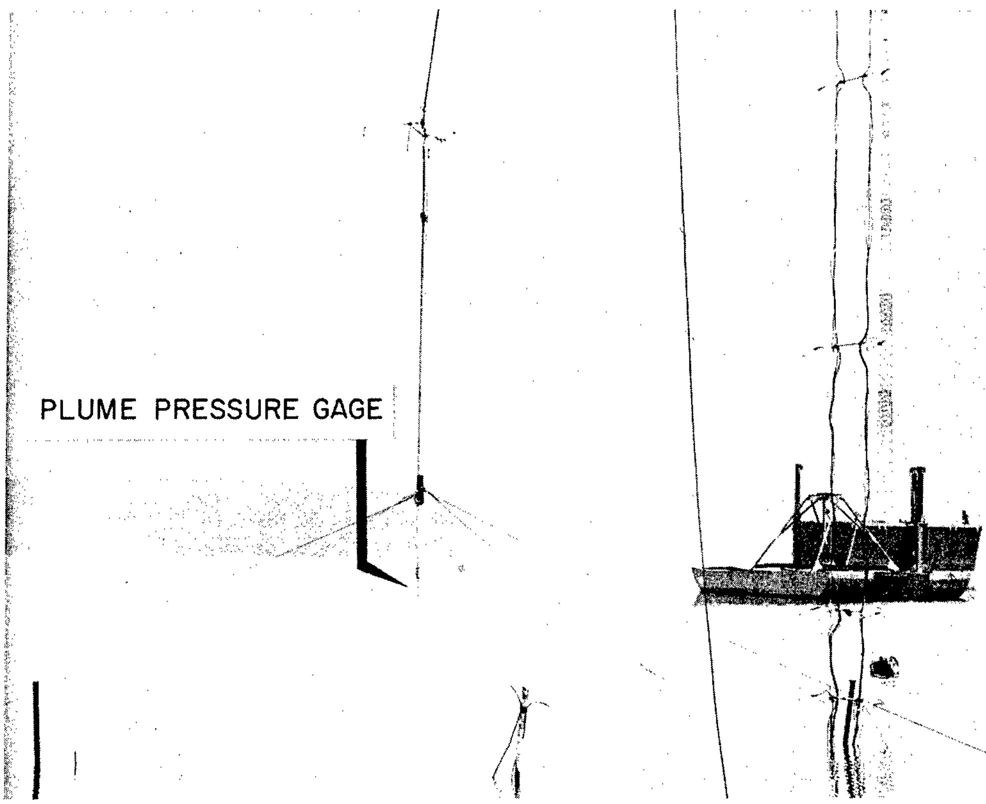


FIG. 7 PLUME PRESSURE GAGE

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Knowledge of the internal structure of the water column produced by a shallow underwater nuclear explosion and of the blowout of explosion products is needed for the calculation of radiological and air shock effects. A piezoelectric gage is proposed to study the internal column structure and blowout on scaled high explosive tests. The different parameters which the gage will sense as pressure changes are discussed. Design requirements and plans for use of such a gage are summarized.

1. Explosions, Underwater
2. Explosions, Atomic
3. Explosives, High
4. Explosions - Blowout
5. **Explosions - Shock effects**
6. Gages, Piezoelectric

I. Title
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III. Phillips, Donald E., jt. author
IV. Project

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